The delicate balance between soil production and erosion, and its role on landscape evolution

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Abstract

The diversity in landscapes at the Earth's surface is the result, amongst other things, of the balance (or imbalance) between soil production and erosion. While erosion rates are well constrained, it is only recently that we are able to quantify rates of soil production. Uranium-series isotopes have been useful to provide such estimates independently of erosion rates. In this study, we present new U-series isotope data from weathering profiles developed over andesitic parent rock in Puerto Rico, and granitic bedrock in southeastern Australia. The site in Australia is located on a highland plateau, neighbouring a retreating escarpment where soil production rates between 10 and 50 mm/kyr were determined. Our results show that production rates are invariant in these two regions of Australia with values between 15 and 25 mm/kyr for the new site. Andesitic soils show much faster rates, about 200 mm/kyr. Overall, soil production rates determined with U-series isotopes range between 10 and 200 mm/kyr. This is comparable to erosion rates in soil-mantled landscapes, but faster than erosion in cratonic areas and slower than in alpine regions and cultivated areas. This suggests that soil-mantled landscapes maintain soil because they can: there is a balance between production and erosion. Similarly, thick weathering profiles develop in cratonic areas because, despite of slow erosion rates, soil production is still significant. Bare landscapes in Alpine regions are probably the result of the inability of soil production to catch up with fast erosion rates, although this needs testing by U-series isotope studies of these regions. Finally, the range of production rates is up to several orders of magnitude lower than erosion rates in cultivated areas, demonstrating quantitatively the fast depletion of soil resources with common agricultural practices.

1. Introduction

Compared to other planets of the solar system, the Earth is characterized by a rich variety of landscapes: bare rocks of active mountain ranges through soil-mantled rolling hills to deeply weathered lowlands. This diversity is the result of a complex interaction between the Earth's surface and tectonics, climate and more recently humans. One main interest in Earth sciences is to understand how these landscapes form and evolve, what controls them, but also how humans affect them. Over the last two decades, the emergence of isotopic techniques (cosmogenic nuclides, uranium-series isotopes) has allowed us to quantify rates of geomorphic processes and shed new light on our understanding of landscape evolution. In particular, uranium-series (U-series) isotopes can be used to determine the soil residence time, i.e. the time elapsed since conversion from bedrock to soil in each horizon of a weathering profile. This can be used in turn to estimate rates of soil production. Previous works have shown that in granitic terrains, soil production rates vary between about 20 to 80 mm/kyr (Dequincey et al., 2002; Dosseto et al., 2007; Dosseto et al., 2008; Mathieu et al., 1995). These studies focused on lateritic profiles in tropical lowlands (Dequincey et al., 2002; Mathieu et al., 1995), actively eroding tropical island (Dosseto et al., 2007) and retreating escarpment under temperate climate (Dosseto et al., 2008). In a recent study, U-series isotopes were used to infer soil production rates over shales in temperate eastern US and yielded values similar to granitic profiles between 17 and 45 mm/kyr (Ma et al., 2007). Here, we measured U-series isotopes in profiles developed over granitic bedrock in temperate southeastern Australia and andesitic bedrock in tropical Puerto Rico. The site in Australia is located on a highland plateau, west of the retreating escapement studied in (Dosseto et al., 2008). The U-series isotope composition of soil samples is used to determine soil residence times throughout the profiles (see below for details) and estimate production rates. Note that this approach does not require knowledge of erosion rates or assuming steady-state thickness of the soil profile.

2. Results

Frogs Hollow, the study site in southeastern Australia, is located on a highland plateau that drains into the Murrumbidgee River, a major tributary of the Murray-Darling River. Soil-mantled hillslopes are underlain by granodiorite. At this site, Heimsath et al. (2001) determined soil denudation rates with cosmogenic nuclides. These rates were used in turn to estimate soil production rates (assuming steady-state soil thickness). Samples were collected in four profiles on ridgetops to avoid contribution of upslope soil by creep. Soil thickness is only a few tens of cm, underlain by several tens of meters of saprolite. In Puerto Rico, the studied area is located in the Bisley catchment, in the Luquillo Mountains. The weathering profile investigated is on a ridge, surrounded by steep slopes, and underlain by marine-deposited basaltic to andesitic volcanoclastics. Soil is 0.8-1.0 m thick, overlying more than 16 m of saprolite. Soil samples were collected at regular intervals. They were processed for U-series isotope analysis using procedures described in (Dosseto et al., 2006; Dosseto et al., 2008) and ^{238}U, ^{234}U and ^{230}Th and ^{232}Th were analysed by multi-collector ICP-MS (Sims et al., 2008).

A possible model to describe the evolution of U-series isotopes in weathering profiles is to consider that their abundance varies with time as a function of radioactive decay, loss through mineral dissolution and gain through either illuviation, dust deposition or both:

$$\frac{dN_j}{dt} = \lambda_i.N_i - \lambda_j.N_j + f_j.N_{j,0} - k_j.N_j \tag{1}$$

where λ_i is the decay constant of the parent nuclide, N_i the abundance of the parent nuclide in the sample, λ_j the decay constant of the nuclide j, f_j an input coefficient for the nuclide j (in yr^{-1}), $N_{j,0}$ the initial nuclide abundance and k_j a dissolution coefficient for the nuclide j (in yr^{-1}). The input and dissolution coefficients are the time constants at which nuclide addition *via* chemical illuviation and/or dust input and removal *via* chemical weathering occur, respectively. These coefficients represent the different rates at which nuclide gain and loss operate. The coefficients may take different values for each nuclide, but they are assumed to be constant throughout the profile and over the soil residence time, T_{res}, i.e. the time elapsed since the inception of bedrock weathering. T_{res} will be different for each soil sample. Thus, we look for the set of k and f coefficients for the weathering profile, and T_{res} values for each sample that best reproduce the observed compositions. This is performed using a genetic algorithm in Matlab™ and generating a large population of solutions. Thus we obtain a probability density function of solutions for the model. We retain the median of this distribution and the error on T_{res} and coefficients is the standard error on the distribution.

At both sites, radioactive disequilibria (i.e. activity ratios different than 1) increase relatively linearly with decreasing depth (Fig. 1). This suggests that soil residence time increases with decreasing depth, as expected since the weathering front migrates downward into the parent rock. At Frogs Hollow, soil residence times up to 30 kyr are inferred using the model described above. In a plot of soil residence time versus depth (Fig. 2), the slope of the linear regression through the data yields the average soil production rate. For Frogs Hollow, soil production rates for the different profiles range between 15 and 25 mm/kyr. At Bisley, residence times increase linearly with decreasing depth (Fig. 2). Calculations suggest it took 70-90 kyr to develop this 18m-thick profile. The average soil production rate is inferred to be 211 ± 37 mm/kyr.

3. Discussion

At both study sites, positive linear relationships are observed between soil residence time and depth. This implies that the rate of downward migration of the weathering front (i.e. soil production) was relatively constant over the time required to develop the profile (i.e. the oldest residence time: 30 kyr for Frogs Hollow, 90 kyr for Bisley). Moreover, the continuous evolution of U-series isotope compositions with depth suggests that bioturbation has little impact at least on U-series (otherwise no systematic variation with depth should be observed). The two Australian sites (this study and (Dosseto et al., 2008)) show similar production rates although located in different geomorphic settings (highland plateau for Frogs Hollow, retreating escarpment in (Dosseto et al., 2008)).

The range of soil production rates inferred from U-series isotope studies spans between 10 and 200 mm/kyr (Fig. 3). Interestingly, different climatic zones seem to be characterized by similar production rates, suggesting that current climatic conditions may have little control on soil production. Moreover, granitic and shale lithologies appear to be converted into soil at similar rates. However, soils are produced faster over volcanic than granitic lithologies for same tropical conditions.

Overall, the range of soil production rates is similar to that of erosion rates in soil-mantled landscapes (Fig. 4). Nevertheless, soil production is faster than erosion in cratonic areas and slower than in Alpine regions. This could imply that soil-mantled landscapes are so because they can maintain a soil cover, i.e. there is a balance between production and loss. Furthermore, thick weathering profiles in cratonic areas may be explained as rates of soil production remain relatively high for these slow eroding regions, i.e. despite of a low supply of fresh minerals, the weathering front continues its downward migration at a sustained rate. Similarly, it is possible that the bare landscape of Alpine regions is the result of an inability for soil production to increase and match erosion rates in actively eroding mountain ranges. However, this hypothesis needs to be tested by U-series isotope studies of mountainous regions, which are lacking at present.

Finally, inferred soil production rates are much lower than erosion rates in cultivated areas. This difference is up to several orders of magnitude and emphasizes how common agricultural practices impact and deplete soil resources.

4. Conclusions

- Increasing radioactive disequilibria with decreasing depth confirm an increase in soil residence time from bottom to top of weathering profiles. Also, continuous patterns suggest little impact of bioturbation on U-series isotope compositions.
- Soil residence times up to 30 and 90 kyr are calculated for Frogs Hollow (Australia) and Bisley (Puerto Rico), respectively. These values are used to infer average soil production rates of 15-25 and 211 mm/kyr, respectively.
- Soil production rates are relatively similar for granitic and shale lithologies, but much higher over volcanic parent rock. For granitic bedrocks, similar values are observed for sites under very different present climatic conditions. This emphasizes that lithology is the primary control on soil production, over climate.
- Soil production matches erosion in soil-mantled landscapes, demonstrating quantitatively that this type of landscape results from a balance between these two processes, and any imbalance between them could explain other types of landscape (cratons and Alpine regions).
- Soil production is up to two orders of magnitude slower than erosion in cultivated areas. This shows quantitatively how fast soil resources are depleted when common agricultural practices are employed.

Ackowledgements.

We would like to thank the organizers of the Symposium of the Geochemistry of the Earth's Surface (GES-9) for the opportunity to present this work. We would also like to thank Barbara Jessup for comments on an earlier version of the manuscript, as well as Francois Chabaux, Sue

Brantley, Arjun Heimsath, Lin Ma and Doug Burbank for useful and inspiring discussions. Dosseto acknowledges an Australian Research Council Future Fellowship. Suresh acknowledges a Macquarie University Research Scholarship. This work was funded by an Australian Research Council Future Fellowship grant FT0990447.

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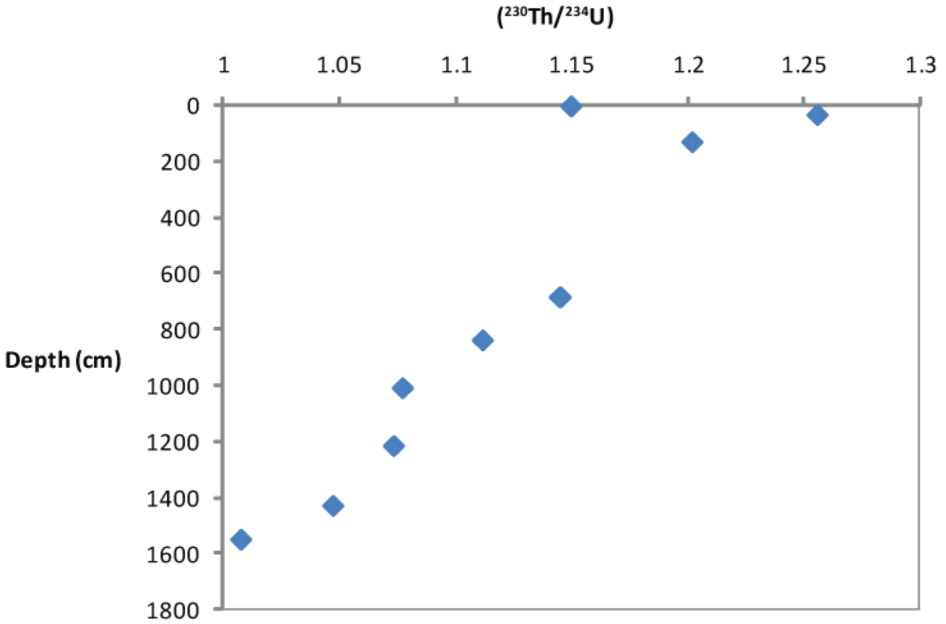

Figure 1. (^{230}Th/^{234}U) activity ratios in soil versus depth (in cm) for the Bisley profile.

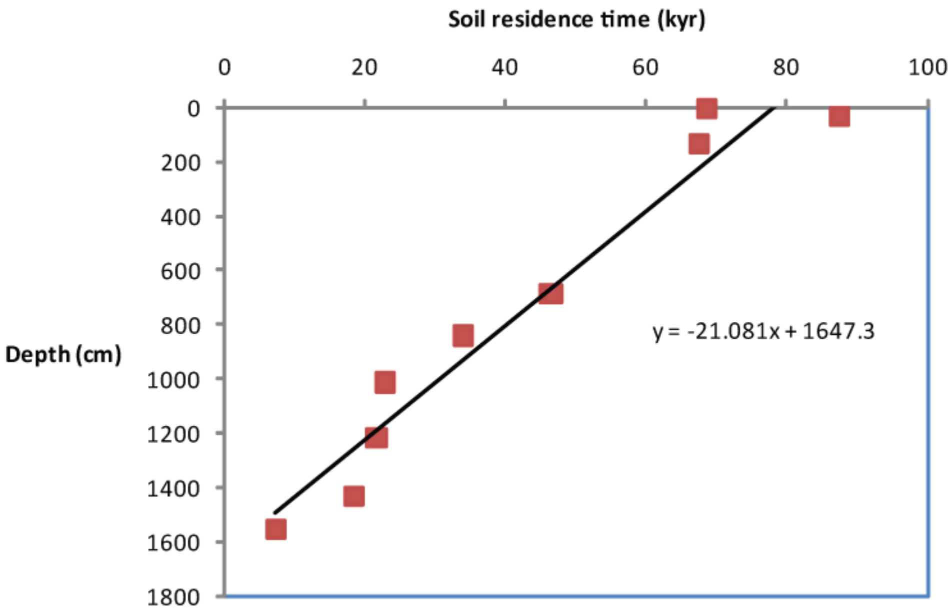

Figure 2. Calculated soil residence time (in 1,000 years) as a function of depth (in cm) for the Bisley profile.

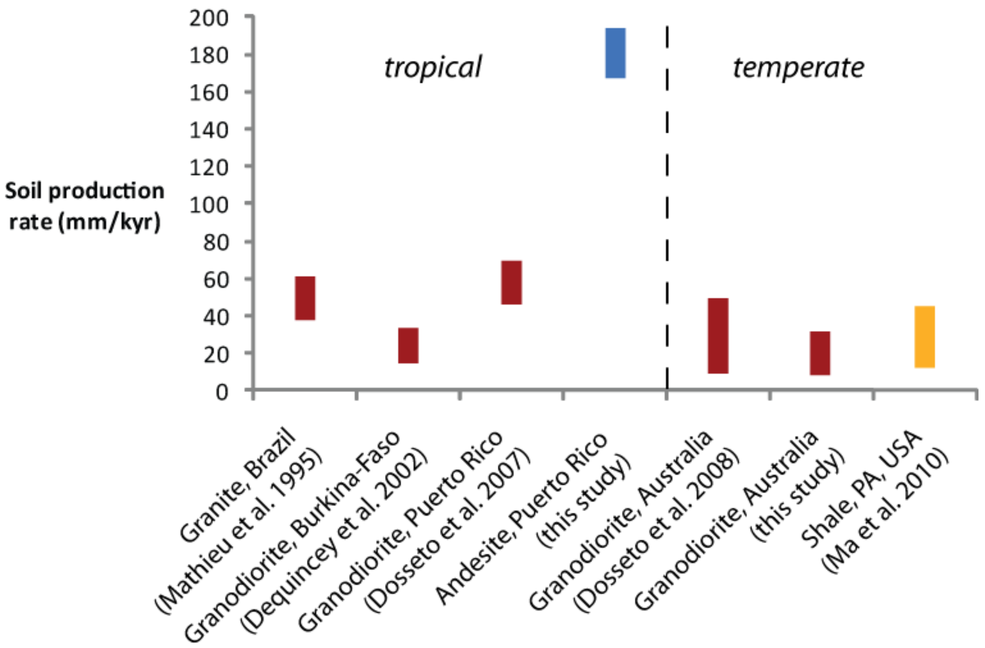

Figure 3. Comparison of soil production rates derived from U-series isotopes in various settings (range of values are shown). Soil production over granitic rocks is relatively insensitive to climate. Whilst shales and granitic rocks apparently produce soils at similar rates, andesitic lithologies produce soil much faster. For same climatic conditions (compare with granodiorite lithology in Puerto Rico), soil is produced 3 times faster over andesite than over granodiorite. Data are from this study and (Dequincey et al., 2002; Dosseto et al., 2007; Dosseto et al., 2008; Ma et al., 2010; Mathieu et al., 1995).

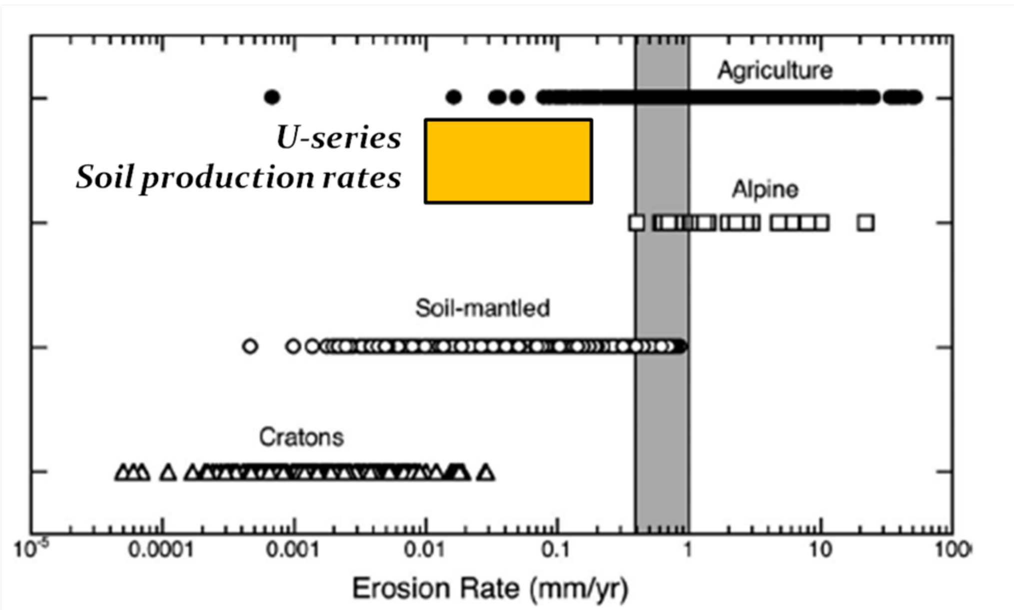

Figure 4. Soil production rates inferred from U-series isotopes compared to erosion rates in various settings. Shaded vertical bar represents the range in soil erosion rates of the US Department of Agriculture. Modified from (Montgomery, 2007).